

# Lepton-flavor violation with Rayleigh operators

Cody Grant

Wayne State University  
July 14<sup>th</sup>, 2021

w/ Alexey A. Petrov



# Outline

- Introduction: lepton flavor violation (LFV)
- Rayleigh operators and muon to electron transition
- Rayleigh Operators in  $e^+ e^-$  collisions



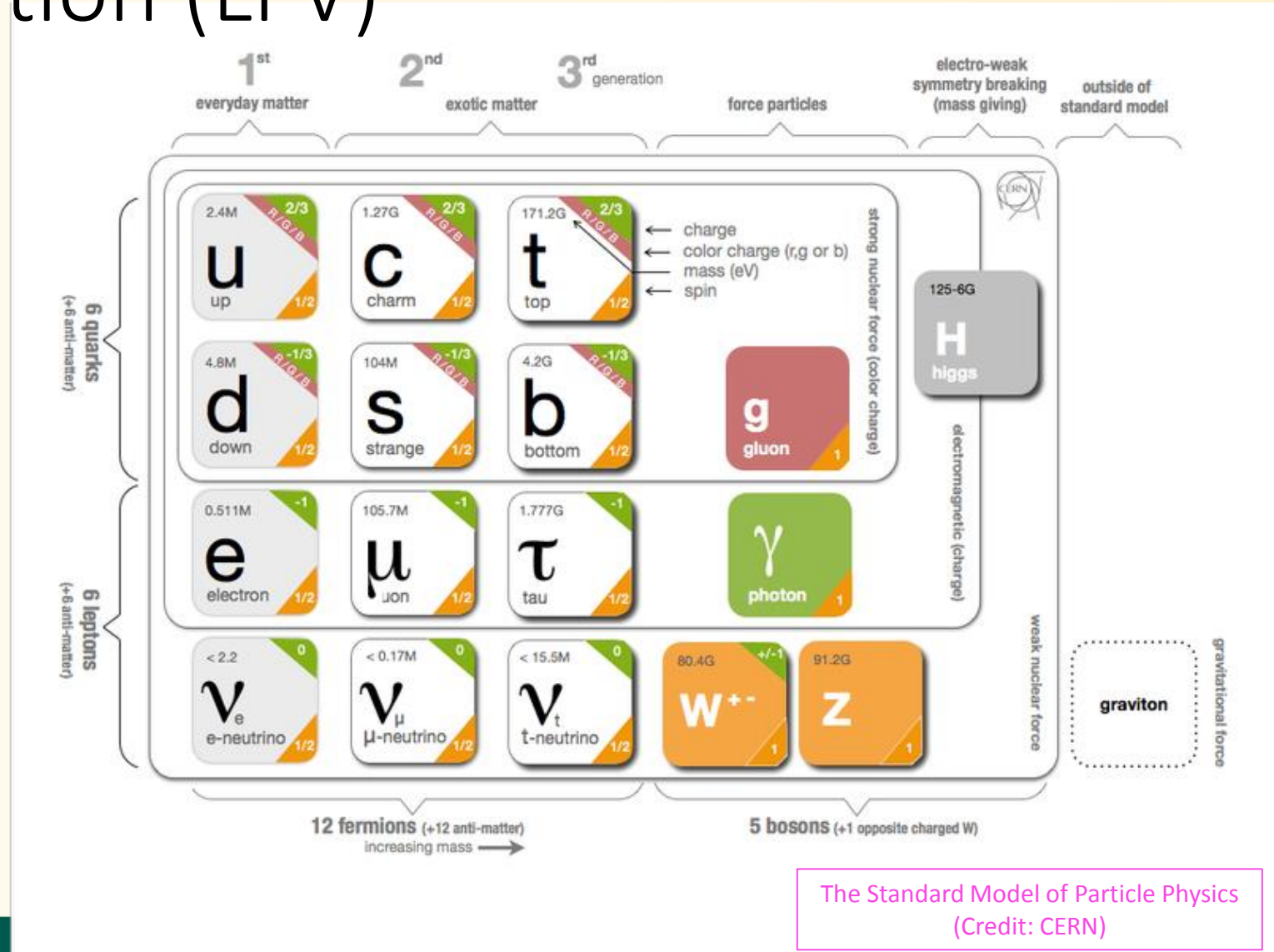
# Lepton Flavor Violation (LFV)

- LFV is heavily suppressed in SM
  - Probe new physics with almost no background



# Lepton Flavor Violation (LFV)

- LFV is heavily suppressed in SM
  - Probe new physics with almost no background
- Neutral current transitions between Generations
  - 1st to 2nd

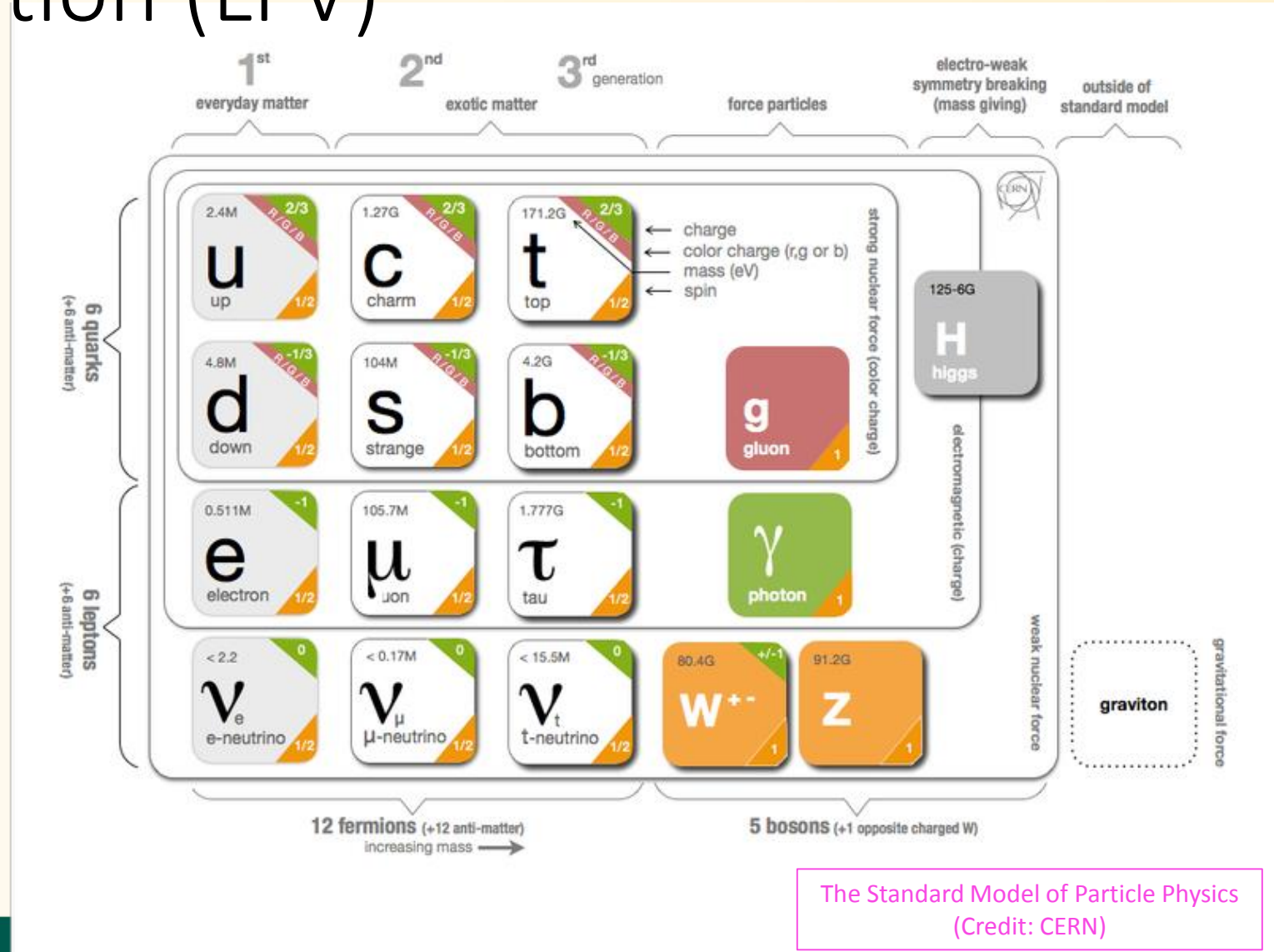


The Standard Model of Particle Physics  
(Credit: CERN)



# Lepton Flavor Violation (LFV)

- LFV is heavily suppressed in SM
  - Probe new physics with almost no background
- Neutral current transitions between Generations
  - 1st to 2nd
  - 2nd to 1st

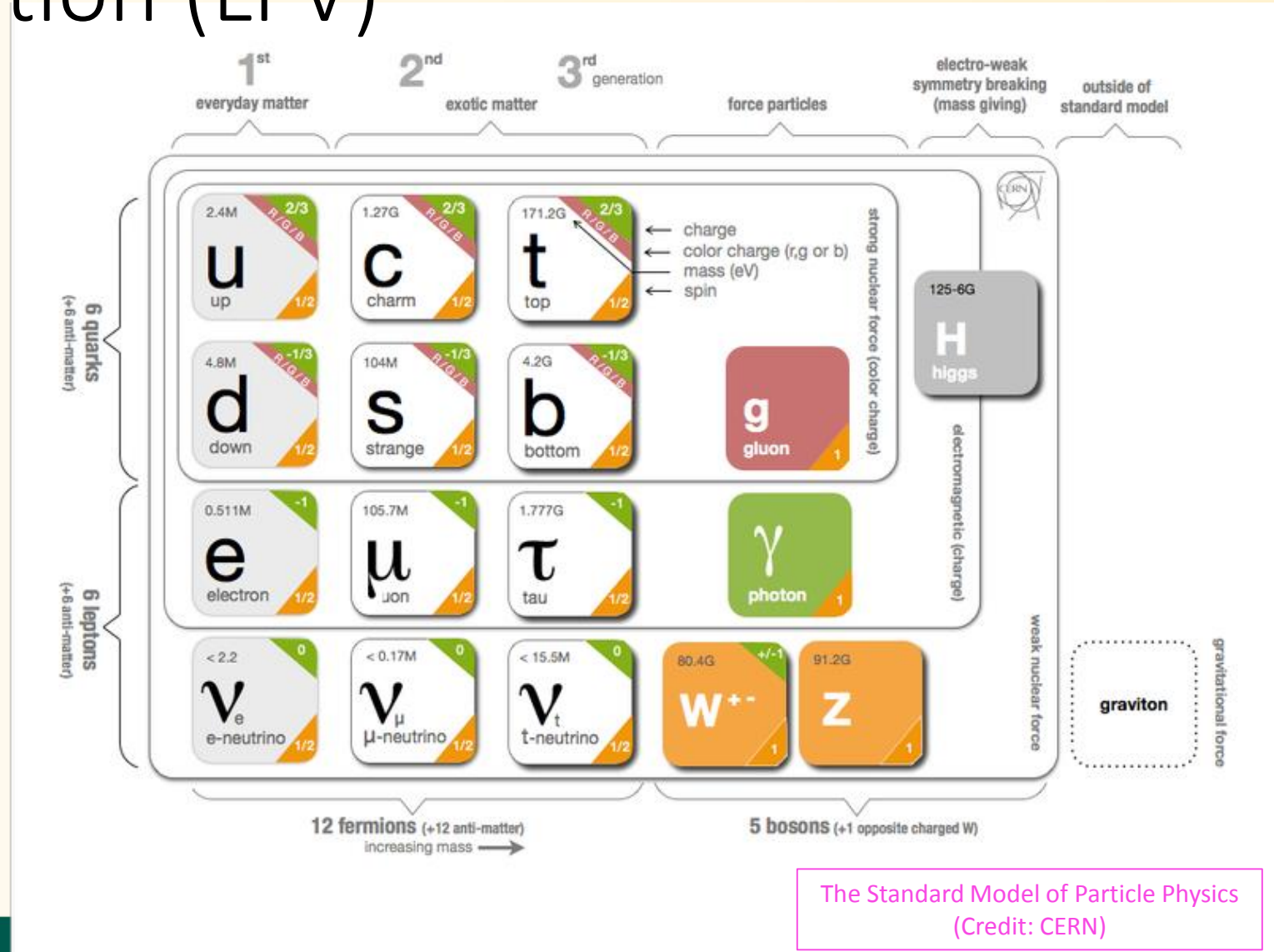


The Standard Model of Particle Physics  
(Credit: CERN)



# Lepton Flavor Violation (LFV)

- LFV is heavily suppressed in SM
  - Probe new physics with almost no background
- Neutral current transitions between Generations
  - 1st to 2nd
  - 2nd to 1st
  - 3rd to 1st

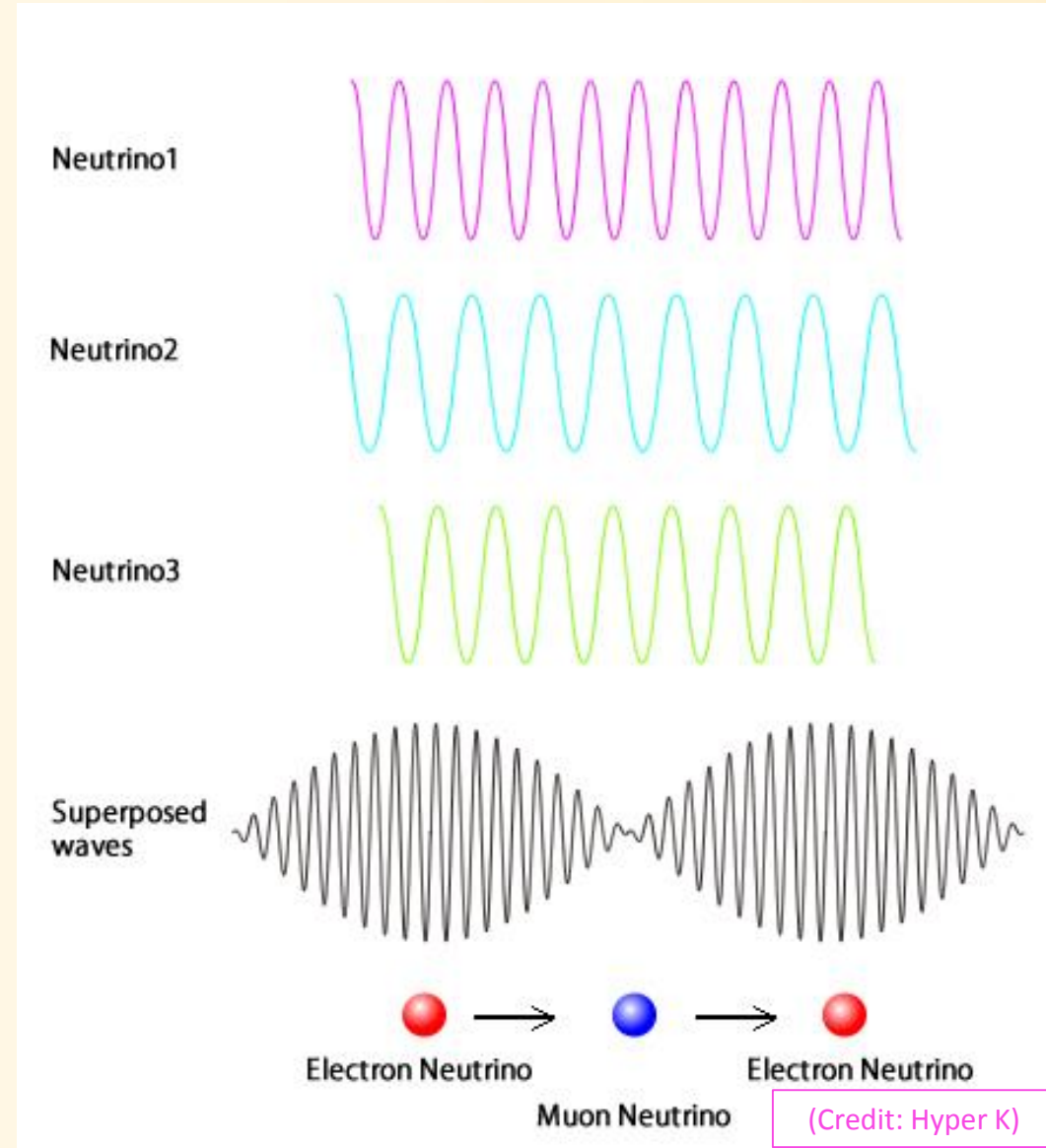
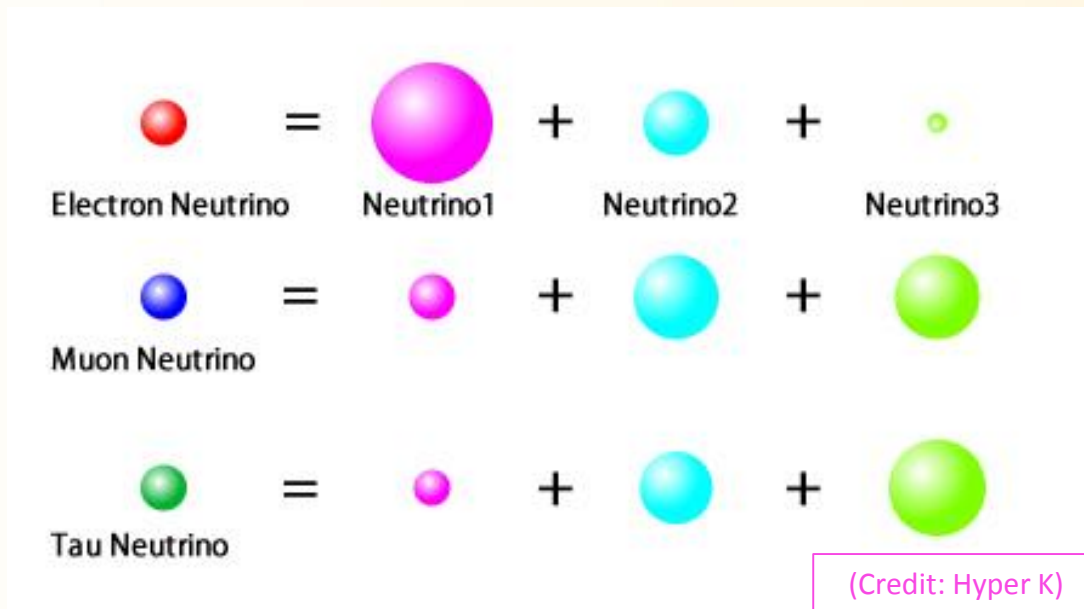


The Standard Model of Particle Physics  
(Credit: CERN)



# LFV in neutrinos

- Well measured in experiment
  - Neutrino Oscillations (PMNS matrix)
    - We measure them in the mass basis:  $\nu_1, \nu_2, \nu_3$
    - But they interact in the weak (flavor) basis:  $\nu_e, \nu_\mu, \nu_\tau$



# LFV in $\mu$ to $e$ transition

- Several different ways that have been studied
  - $\mu \rightarrow 3e$                       ( $< 10^{-12}$  [SINDRUM])                      ( $\sim 10^{-16}$  [Mu3e])



# LFV in $\mu$ to $e$ transition

- Several different ways that have been studied

• $\mu \rightarrow 3e$	( $< 10^{-12}$ [SINDRUM])	( $\sim 10^{-16}$ [Mu3e])
• $\mu \rightarrow e \gamma$	( $< 4.2 * 10^{-13}$ [MEG])	( $\sim 10^{-14}$ [MEG II])



# LFV in $\mu$ to $e$ transition

- Several different ways that have been studied

- $\mu \rightarrow 3e$  ( $< 10^{-12}$  [SINDRUM]) ( $\sim 10^{-16}$  [Mu3e])
- $\mu \rightarrow e \gamma$  ( $< 4.2 \cdot 10^{-13}$  [MEG]) ( $\sim 10^{-14}$  [MEG II])
- $N + \mu \rightarrow N + e$  ( $< 7 \cdot 10^{-13}$  [SINDRUM II]) ( $\sim 10^{-16}$  [COMET, Mu2e])  
( $\sim 10^{-18}$  [PRISM, PRIME])



# LFV in $\mu$ to $e$ transition

- Several different ways that have been studied
  - $\mu \rightarrow 3e$  ( $< 10^{-12}$  [SINDRUM]) ( $\sim 10^{-16}$  [Mu3e])
  - $\mu \rightarrow e \gamma$  ( $< 4.2 \cdot 10^{-13}$  [MEG]) ( $\sim 10^{-14}$  [MEG II])
  - $N + \mu \rightarrow N + e$  ( $< 7 \cdot 10^{-13}$  [SINDRUM II]) ( $\sim 10^{-16}$  [COMET, Mu2e])  
( $\sim 10^{-18}$  [PRISM, PRIME])
  - $\mu \rightarrow e 2\gamma$  ( $< 7.2 \cdot 10^{-11}$  [Crystal Box])



# LFV in $\mu$ to $e$ transition

- Several different ways that have been studied
  - $\mu \rightarrow 3e$  ( $< 10^{-12}$  [SINDRUM]) ( $\sim 10^{-16}$  [Mu3e])
  - $\mu \rightarrow e \gamma$  ( $< 4.2 \cdot 10^{-13}$  [MEG]) ( $\sim 10^{-14}$  [MEG II])
  - $N + \mu \rightarrow N + e$  ( $< 7 \cdot 10^{-13}$  [SINDRUM II]) ( $\sim 10^{-16}$  [COMET, Mu2e])  
( $\sim 10^{-18}$  [PRISM, PRIME])
  - $\mu \rightarrow e 2\gamma$  ( $< 7.2 \cdot 10^{-11}$  [Crystal Box])
- Davidson et. al. proposal: Flavor changing Rayleigh operators (RO)
  - $N + \mu \rightarrow N + e$ 
    - Flavor violating interaction:  $\mu \rightarrow e 2\gamma$ 
      - Experimental branching ratio cutoff isn't too small:  $\sim 10^{-11}$

Davidson, Kuno, Uesaka,  
and Yamanaka (DKUY)  
ArXiv: 2007.09612 [hep-ph]



# Proposal by Davidson et. al. (DKUY)

$$\mathcal{L} = \frac{1}{v^3} \left( C_{FF,L} \bar{e} P_L \mu F_{\alpha\beta} F^{\alpha\beta} + C_{FF,R} \bar{e} P_R \mu F_{\alpha\beta} F^{\alpha\beta} + C_{F\tilde{F},L} \bar{e} P_L \mu F_{\alpha\beta} \tilde{F}^{\alpha\beta} + C_{F\tilde{F},R} \bar{e} P_R \mu F_{\alpha\beta} \tilde{F}^{\alpha\beta} \right)$$

- Mass scale of operators:  $v \sim 200$  GeV
  - This is not experimentally excluded
- Lepton flavor transition in a classical electric field generated by an atomic nucleus
  - $\pi^0$  current is negligibly small as it's coupled to  $\mathbf{E} \cdot \mathbf{B}$
- Matched two-photon operators to heavy fermion scalar operators

$$\frac{C_{FF,X}}{v^3} = - \sum_{\psi} (C_{S,XX}^{\psi\psi} + C_{S,XY}^{\psi\psi}) \frac{Q_{\psi}^2 N_c \alpha_e}{12\pi m_{\psi} \Lambda_{NP}^2}$$



# Rayleigh operators in $e^+ e^-$ collisions

- Collision has a clean environment
- Current running experimentally (Belle II)
- For the process:  $e^+ e^- \rightarrow \mu^+ e^- \gamma$ 
  - Use the same "short-range" (SR) vertex/operator:  $\mu \rightarrow e 2\gamma$



# LFV Raleigh operators & SM e+e- collisions

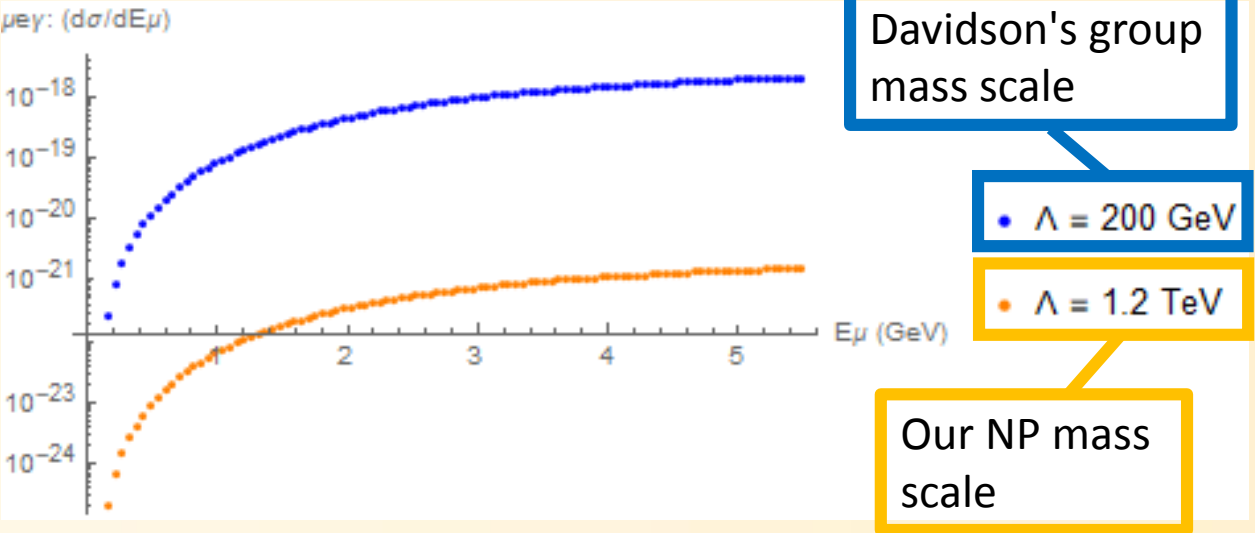
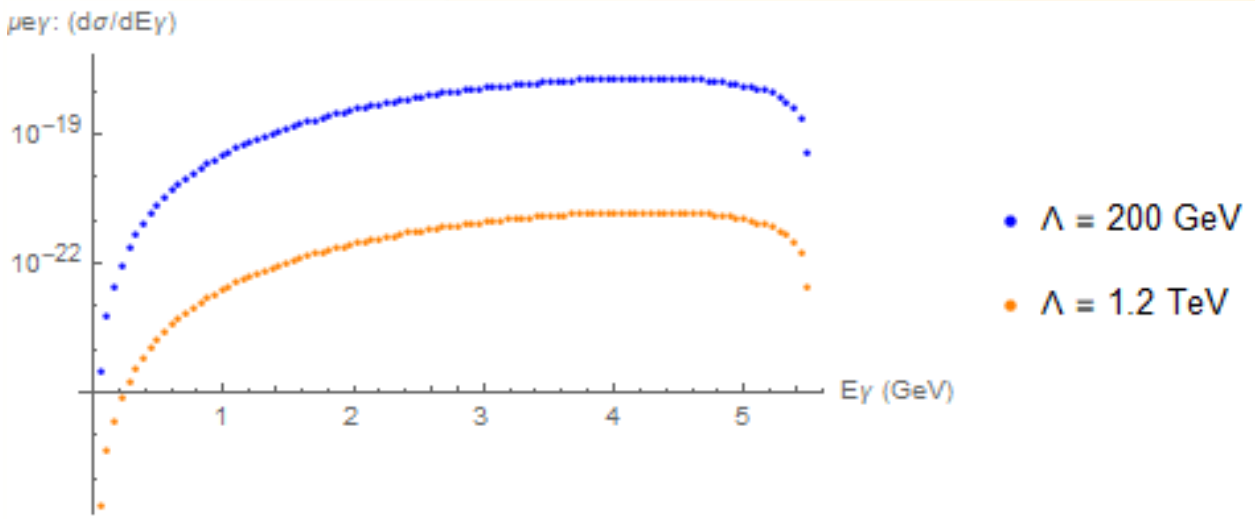
- Double differential cross section for the SR process

- $d^2\sigma_{SR}/dE_\mu dE_\gamma = (\alpha^3 Q_c^4 / m_c \Lambda^4) 4E_\gamma^3 |p_\mu| (s - m_\mu^2 - 2E_\gamma s^{1/2}) / (48 \pi^5 s) (C_S^2 + \dots)$



# LFV Raleigh operators & SM e+e- collisions

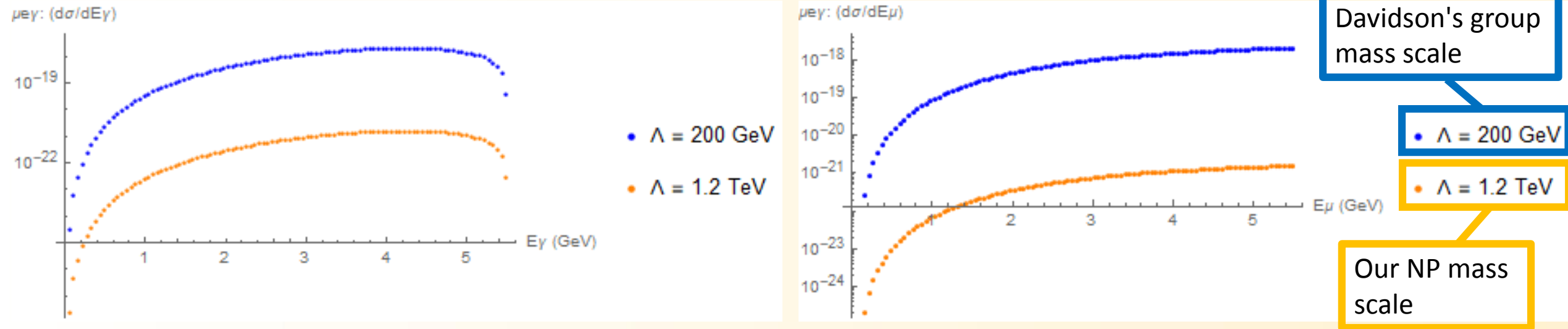
- Double differential cross section for the SR process
  - $d^2\sigma_{SR}/dE_\mu dE_\gamma = (\alpha^3 Q_c^4 / m_c \Lambda^4) 4E_\gamma^3 |p_\mu| (s - m_\mu^2 - 2E_\gamma s^{1/2}) / (48 \pi^5 s) (C_S^2 + \dots)$



# LFV Raleigh operators & SM e+e- collisions

- Double differential cross section for the SR process

$$\bullet \frac{d^2\sigma_{SR}}{dE_\mu dE_\gamma} = (\alpha^3 Q_c^4 / m_c \Lambda^4) 4E_\gamma^3 |p_\mu| (s - m_\mu^2 - 2E_\gamma s^{1/2}) / (48 \pi^5 s) (C_S^2 + \dots)$$



- Comparing to total cross section (e e -> μ μ)

$$\bullet \sigma_{ee \rightarrow \mu\mu} = 4\pi\alpha^2 (s - 4m_\mu^2)^{1/2} (2m_\mu^2 + s) / (3s^{5/2})$$



# Rayleigh operators in $e^+ e^-$ collisions

- Possible long-range contributions to the same process
  - Propagating  $\pi^0$  meson
    - Pion to 2 photons (one virtual)

Xiao and Ma  
ArXiv: 0312162 [hep-ph]

$$\Gamma_\mu = -ie^2 F_{\gamma^* \pi \rightarrow \gamma}(Q^2) \varepsilon_{\mu\nu\rho\sigma} p_\pi^\nu \epsilon^\rho q^\sigma$$



# Rayleigh operators in e+ e- collisions

- Possible long-range contributions to the same process
  - Propagating  $\pi^0$  meson
    - Pion to 2 photons (one virtual)
  - Propagating  $\rho^0$  meson
    - Vector Meson Dominance

Xiao and Ma  
ArXiv: 0312162 [hep-ph]

$$\Gamma_\mu = -ie^2 F_{\gamma^*\pi\rightarrow\gamma}(Q^2) \varepsilon_{\mu\nu\rho\sigma} p_\pi^\nu \epsilon^\rho q^\sigma$$

Golowich and Pakvasa  
Phys Rev D 51 (3) (1995)

$$\mathcal{L}_{\text{VMD}} = \frac{e}{f_V} \left[ \frac{1}{2} F_{\mu\nu} V^{\mu\nu} + J_\mu^V A^\mu \right]$$



# Rayleigh operators in $e^+ e^-$ collisions

- Possible long-range contributions to the same process

Xiao and Ma  
ArXiv: 0312162 [hep-ph]

- Propagating  $\pi^0$  meson
  - Pion to 2 photons (one virtual)

$$\Gamma_\mu = -ie^2 F_{\gamma^* \pi \rightarrow \gamma}(Q^2) \epsilon_{\mu\nu\rho\sigma} p_\pi^\nu \epsilon^\rho q^\sigma$$

Golowich and Pakvasa  
Phys Rev D 51 (3) (1995)

- Propagating  $\rho^0$  meson
  - Vector Meson Dominance

$$\mathcal{L}_{\text{VMD}} = \frac{e}{f_V} \left[ \frac{1}{2} F_{\mu\nu} V^{\mu\nu} + J_\mu^V A^\mu \right]$$

Hazard and Petrov  
ArXiv: 1607.00815 [hep-ph]

- Meson transition to lepton pair

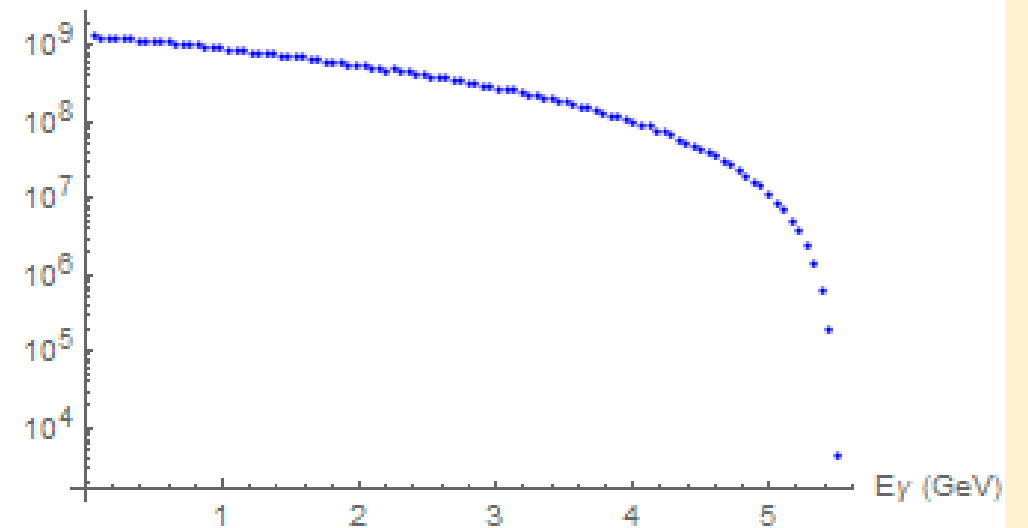
$$\begin{aligned} \mathcal{L}_{lq} = & -\frac{1}{\Lambda^2} \sum_q \left[ \left( C_{VR}^{ql_1 l_2} \bar{l}_1 \gamma^\mu P_R l_2 + C_{VL}^{ql_1 l_2} \bar{l}_1 \gamma^\mu P_L l_2 \right) \bar{q} \gamma_\mu q \right. \\ & \left. + \left( C_{AR}^{ql_1 l_2} \bar{l}_1 \gamma^\mu P_R l_2 + C_{AL}^{ql_1 l_2} \bar{l}_1 \gamma^\mu P_L l_2 \right) \bar{q} \gamma_\mu \gamma_5 q \right] \end{aligned}$$



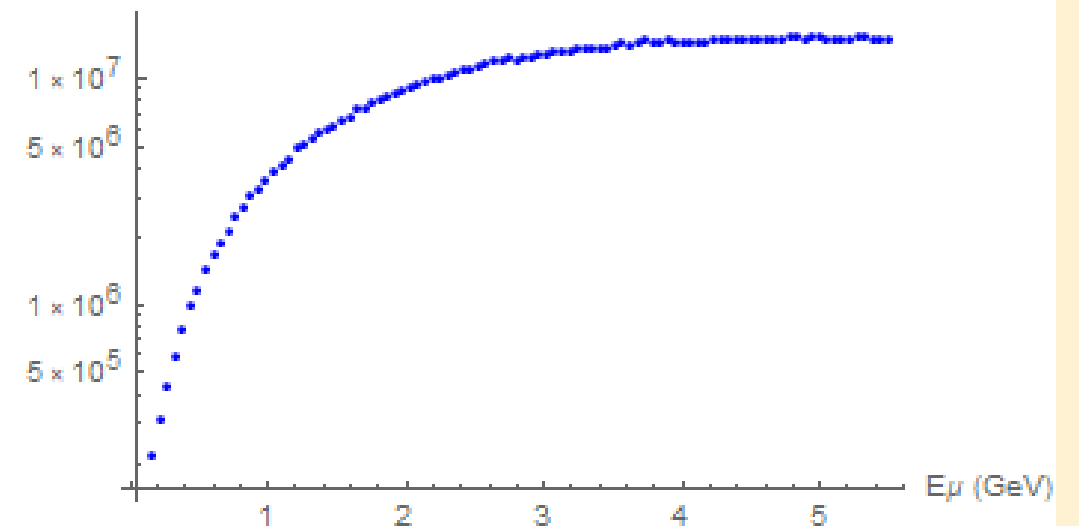
# Long distance effect: $\pi^0$

- $SR \propto (\alpha^3/\Lambda^4) \Sigma C_{SR}^2$
- $\pi^0 \propto (\alpha^3/\Lambda^4) (C_{AL}^2 + C_{AR}^2)$
- $(d\sigma_{SR}/dE_\mu) / (d\sigma_\pi/dE_\mu)$ 
  - Assuming Ratio of Wilson Coeff:  $\Sigma C_{SR}^2 / (C_{AL}^2 + C_{AR}^2)$  is  $\sim O(1)$

SR/ $\pi^0$  ratio:  $(d\sigma/dE_\gamma)$



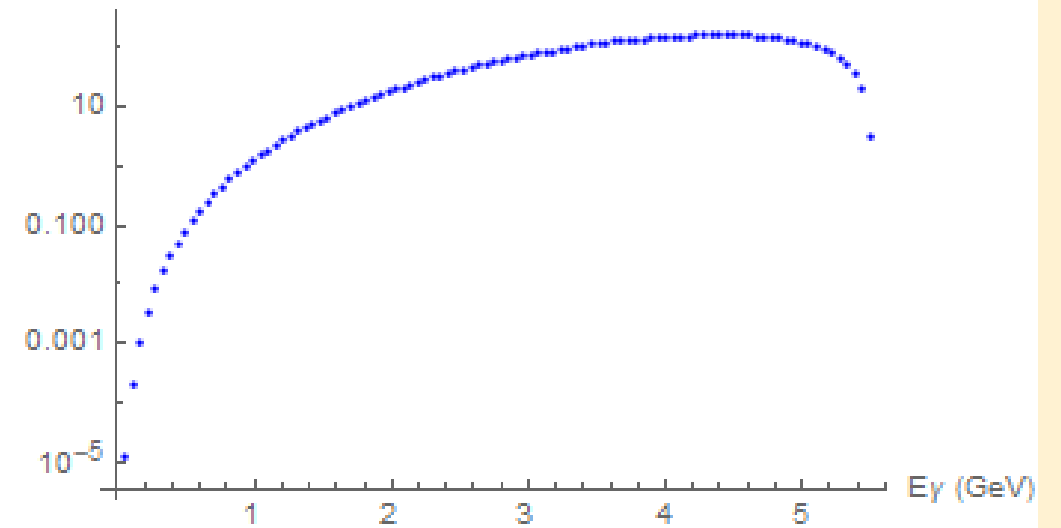
SR/ $\pi^0$  ratio:  $(d\sigma/dE_\mu)$



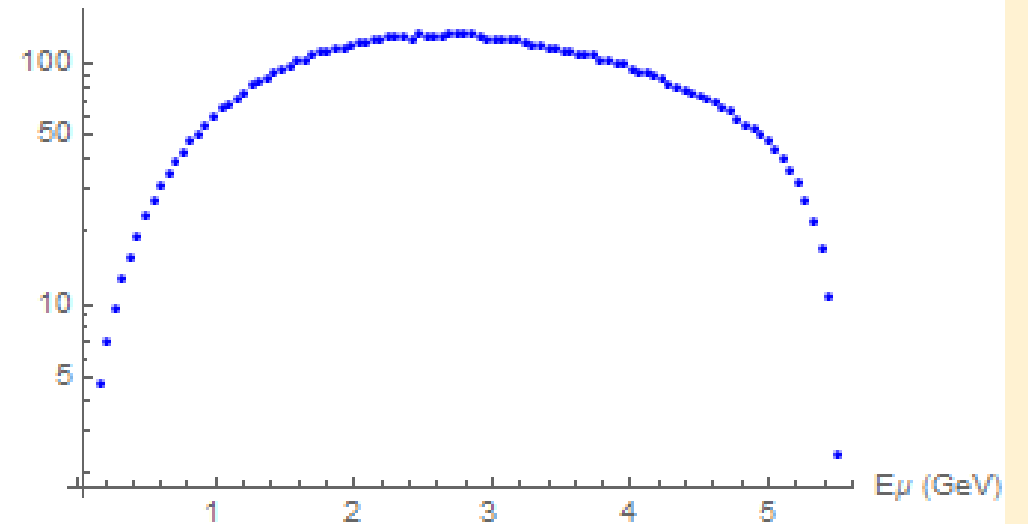
# Long distance effect: $\rho^0$

- $SR \propto (\alpha^3/\Lambda^4) \Sigma C_{SR}^2$
- $\rho^0 \propto (\alpha^3/\Lambda^4) (C_{VL}^2 + C_{VR}^2)$
- $(d\sigma_{SR}/dE_\gamma) / (d\sigma_\rho / dE_\gamma)$ 
  - Assuming Ratio of Wilson Coeff:  $\Sigma C_{SR}^2 / (C_{VL}^2 + C_{VR}^2)$  is  $\sim O(1)$

SR/ $\rho^2$  ratio:  $(d\sigma/dE_\gamma)$



SR/ $\rho^2$  ratio:  $(d\sigma/dE_\mu)$



# Conclusions

- These Rayleigh Operators could be useful to study and probe for LFV violation in electron-positron collisions
  - Needs experimental sensitivity updates as well
- Looking at the short-range vs long-range interactions
  - Long-range effects from the pion is very small compared to short-range interaction
    - $> 10^7$
  - Long-range effects from the rho meson is on the order of the short-range interaction
    - In some energy range, it even dominates

